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What are the right policies for electricity supply in Middle East? A regional dynamic integrated electricity model for the province of Yazd in Iran

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ABSTRACT

Energy planning techniques are essential tools in the management of new complex energy systems. Among different techniques, System Dynamics is an appropriate technique for the simulation of complex energy systems and the analysis of their dynamism. In this paper, a regional dynamic integrated electricity model (RDIEM) is developed for a regulated electricity supply system in order to analyze the results of different scenarios and policies and find the right policies for the electricity generation. The results of model are validated with a real case in the province of Yazd in Iran. The results show that the balanced growth and the environment-oriented policies have the best results among different policies. Although the application is related to the Iranian case, the implications are much wider, especially in the Middle East.

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1. Introduction

The importance of electricity in the new world together with the uncertainties in its future demands has made electricity planning to be a main concern for the electricity consumers and producers in different countries. In recent years, there have been various attempts in the field of energy planning which have led to some novel and valuable models. Depending on their approach to the energy planning problem, these models can be categorized in the following four groups:

- Econometric models: these models are mainly generated based on the econometric techniques. They are long-term or mid-term models with a low level of details having a top-down approach in the analysis of the energy systems. One of the main econometric models is E3MME [1]. The fact that these models do not consider enough details as well as the existing dynamism of energy systems implies that the results of these models do not have enough degree of accuracy.
- Energy equilibrium models: these models, with mid-term or long-term horizon and an almost low level of details, are created based on the equilibrium equations and the game theory principles. The most popular models in this category are ENPEP and SGM [1]. These models have a top-down approach in the analysis of the energy systems. Likewise, the main drawbacks of these models are also the lack of accuracy and the low level of details. In comparison with the econometric models, the equilibrium models consider the dynamism of the energy system to some extent.
- Optimization models: these models, which are created based on the mathematical programming, are short-term or mid-term models with a high level of details. On the contrary to the above-mentioned models, these models have a bottom-up approach. Some of the main optimization models are MARKAL, MESSAGE and EFOM [1–3]. In addition to these well-known and comprehensive models, there are some other optimization models which have had regional applications (for example see [4]). Even though these models have a high level of details, they do not have enough flexibility in dealing with different variables and in the analysis of the dynamisms of the energy systems.
- Simulation-based models: these models are based on the model-based simulation principles. In most cases, these models are short-term or mid-term with the highest amounts of details and a bottom-up approach. These models are the best models in considering the dynamisms of the systems and they have also an acceptable level of accuracy and flexibility in system analysis. As a result of these advantages, the simulation-based models are the most popular models in energy planning. LEAP [5], TIMES [6] and MIDAS [7] are some of the most popular simulation-based models in energy planning. Moreover, there are also some regional energy plans based on the simulation models (e.g. [8]).

Even though, the popular simulation-based models have an acceptable capability to handle the energy systems, they do not have enough flexibility in the number of variables and analyzing the dynamics of the more complex energy systems, especially in the developing countries.

System Dynamics, which is also a simulation-based technique, studies the interactive relationships between variables and makes a good understanding of the considered system. Because of the complexity of energy systems in the developing countries (due to the impact of economic, social, and political factors), SD is an appropriate approach to make a realistic local energy model. While SD has the advantages of the simulation-based models, it also has a great flexibility in facing the complexity of energy systems.

A review of literature showed that the previous applications of SD in electricity energy planning were not inclusive enough as they have not considered all the related subsystems and variables. In other words, these researches have focused on the analysis of some parts of the system such as regulating, price, tariff and demand.

On the other hands, Middle East is one of the main important parts of the world corresponding to the energy issues. The existence of abundant sources of fossil energies with a significant potential in a wide range of renewable energies make it the most effective part of the world in energy market. These valuable potentials have been accompanied with some substantial obstacles in the economical and governmental structure of the Middle East countries, such as oil-based economics, the pale role of private sector in economics and the wide range of subsidies, especially in energy sector. These obstacles with the wide sources of fossil energy in Middle East caused a reluctancy between Middle East countries to invest in renewable sources of energy. The combination of these issues in addition to the environmental problems, make a complex situation for energy planners.

In this study, the system dynamics approach was applied to analyze the Iranian electricity supply system and propose the suitable policies for the role of private sector, the portfolio of energy, the required amount of demand side management programs and research and development programs. For this purpose, a regional dynamic integrated electricity model was developed (RDIEM) and the effectiveness of the model in handling the dynamism of the system and analyzing different scenarios and policies is validated with a real case in the province of Yazd in Iran. The results of the model are evaluated based on different economical, technical and environmental indices.

The rest of the paper is organized as follows: in Section 2, the related publications are reviewed. A brief review on the structure of electricity energy system in Iran is represented in Section 3. Section 4 introduces the main structure of the proposed SD model. In Section 5, the validation of the proposed model and the results of policy analysis are argued. Finally, the concluding remarks are represented in Section 6.

2. Literature review

System Dynamics which was pioneered by Forrester [9] is valued as a strategic tool to analyze the effects of different policies

and scenarios on the system's behavior. This is more advantageous in the analysis of rapidly changing systems with various kinds of risk such as energy systems. The pioneering work in the application of System Dynamics in energy systems was represented by Naill [10] who developed a model for the United States gas industry with a limited number of variables. Similarly, Sterman [11] developed a System Dynamics model with a mutual relationship between energy and economy. Naill, in another study, described the conceptual development of FOSSIL2, which is an integrated model of U.S. energy supply and demand and its application in the energy policy analysis [12]. His conceptual model only focused on the supply and demand relations and had less attention on the other parts of the energy systems. Again, Nail et al. analyzed the effects of U.S. policies in the mitigation of global warming using the FOSSIL2 integrated energy model [13]. Although SD is a useful technique in the analysis of energy systems, there are scarce researches that have considered it, especially in the electricity systems. Moreover, most of the related researches have not considered all of the subsystems in the energy systems.

The first attempts in the application of SD in electricity energy planning were performed by Rahn [14] and Ford [15]. Generally, they represented the conceptual models for electricity provision system with minimum amount of details in their works. In another paper, Moxnes prepared a SD model to analyze the fuel substitution policies in OECD – European electricity production systems [16]. Lomi and Larsen [17] applied SD as a tool to describe different strategic issues and different kinds of risks that newly deregulated power companies are facing. Likewise, Larsen and Bunn analyzed the strategic and regulatory risks that might be happened by deregulation of electricity in UK [18].

Qudratollah [19,20], in two different papers, represented a model for understanding the dynamics of electricity supply, resources and pollution and applied it in Pakistan. In his model named MDESRAP, 4 different scenarios including base case, environment-oriented, market-oriented and self-oriented scenarios were analyzed considering economical and environmental indices. For this purpose, the gross domestic production (GDP) and the amount of CO_2 emission were considered to be the appraisal criteria for a period of 2000–2030. Again Ford in two different papers, applied a computer simulation model based on SD to describe the effects of construction cycles and different patterns on the power plant constructions. He finally concluded that it is more likely that the construction lag behind the growth in demand and the prices climb to surprisingly values in the peak times and after the completion of the power plants, there will be a drop in the wholesale price. He named this behavior as the boom/bust pattern in price [21,22]. Olsina et al. [23] represented a system dynamics model of the liberalized electricity markets and analyze the long term dynamics of them. They showed that the delays in the investment decisions and construction lead to fluctuating reserve margins and consecutively, to volatile long-run market price.

In another paper, Ford used SD as a tool for analyzing different policies in CO2 reduction for western electricity plants in U.S [24]. Kilank and Or [25] presented a SD model, focused on the role of Distributed Generation technologies (DG) on which the results of different scenarios were analyzed. Hasani and Hosseini proposed a decentralized market-based model for long term capacity investment decisions in a liberalized electricity market using System Dynamics [26]. In another research, Trappey et al. developed a cost-benefit evaluation methodology based on System Dynamics modeling for Penghu region in Taiwan to evaluate the renewable energy policies [27]. Recently, Chang et al. [28] used SD to explore the causal relationship of solar water heater installation in Taiwan and simulated relevant government policies. The results show that the continuing government subsidies for the solar power will lead to the development of solar water heater installation. As it can be seen from the abovementioned researches, they have only focused on the causal loop model or the flow model of some parts of the electricity supply system and consequently, it is more likely possible that they have neglected the feedbacks and effects of the other parts of the real system, which they have not considered in their models.

3. Iranian electricity system (Yazd province)

In the electricity provision structure of Iran, there are some regional electricity companies that manage all of the electricity value chain throughout the region. These regional companies have some subordinate companies that deal with supplying, transferring, dispatching and the other parts of electricity system. Up to now, all the parts of electricity value chain are exclusively handled with the government sector. Only in recent years, the private sector has invested in some new power plants, but the share of private sector in electricity supply system is not comparable to the government sector's ones. In addition, the electricity selling tariffs are lower than the total cost of electricity generation. In other words, government sector have paid an enormous amount of subsides for electricity, even after the implementation of recent new rules on subsides. Due to the reasons, the regional electricity companies are not profitable and thoroughly depend on the governmental budget. This problem is getting more crucial when the researches showed that the government- oriented electricity generation in Iran causes a lower energy and capital productivity in comparison with the world average [29].

From another point of view, gas and water have the main contribution in the energy portfolio of electricity generation in Iran. Although, there are remarkable deposits of coal in Iran, the coal-fired power plants have not any share in electricity generation [30]. Moreover, in spite of a great potential in electricity generation with renewable energies such as solar, wind and geothermal, there are little efforts in this area [30]. This concentration on fossil energies in electricity generation, which is a result of the low price of them, leads to crucial problems in economic and environment.

Yazd which is located in central Iran is among the driest cities in Iran, with an average annual rainfall of only 60 mm, with summer temperatures very frequently above 40 °C in blazing sunshine with no humidity. Although, Yazd has the greatest deposits of coal and numerous numbers of sunny days, Gas which is prepared from the southwest regions of Iran (Khuzestan) is the only consumed energy in the electricity generation. Hence, In addition to gas consuming power plants, the coal-fired and solar power plants are the other more applicable ways for the electricity generation in Yazd [31].

4. The proposed RDIEM model

The proposed RDIEM model is consisted of 10 main subsystems. Fig. 1 illustrates the macro-structure of the proposed model with the subsystems and three main exogenous variables. The main exogenous variables in this model are GDP (gross domestic production), inflation rate and technology change which make a remarkable effect on the behavior of the electricity supply system. These variables are considered as outer variables which affect different subsystems, but are not affected by them. As it is shown in Fig. 1, the exogenous variables, the considered subsystems and their main variables have many interactions with each other. They have a lot of direct and contextual influences on different subsystems which are described below.

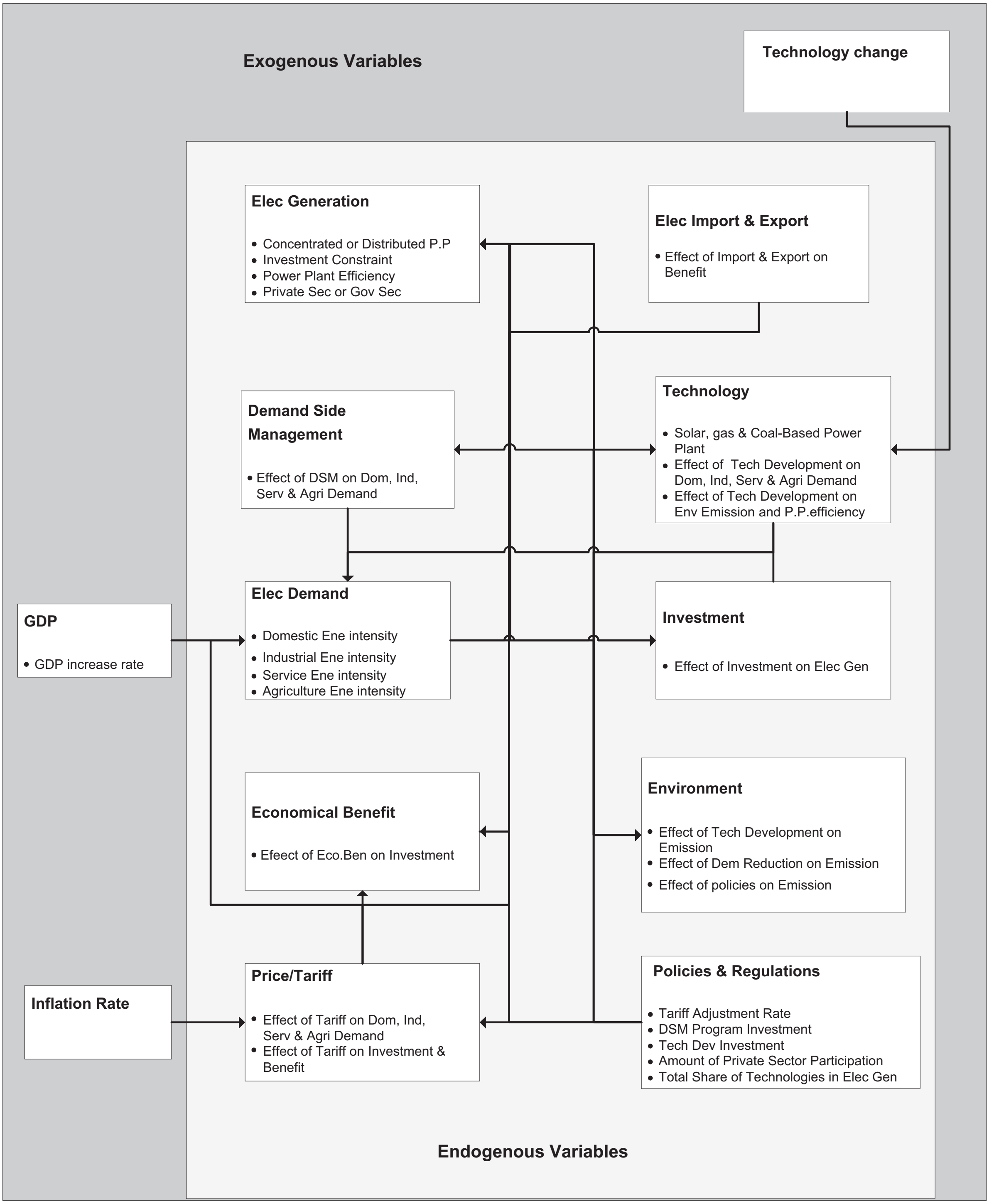

Fig. 1. Macro structure of the proposed SD model.

A brief view of the causal loop diagram (CLD) of the model is represented in Fig. 2; however, the CLD is a good tool to understand the causal relationships between different subsystems and variables, it cannot explain the importance and the magnitude of the relationships; Therefore, corresponding to the causal loop diagram, the stock-flow diagram (SFD) of the electricity supply system is modeled to elaborate the numerical effects of different variables on the system and evaluate the expected behavior of system in respect to the different scenarios and policies. In this paper, for the sake of brevity, we have just focused on the SFD of different subsystems and the detailed explanation of the CLD is removed.

The essential elements of subsystems and their stock flow representations are described as follows.

4.1. Electricity demand subsystem

The main variables of the electricity demand subsystem are as follows:

– ***GDP***: GDP is an index that shows the total amounts of production in different economies. As it is obvious, the amount of energy consumption (especially electricity) has a straight

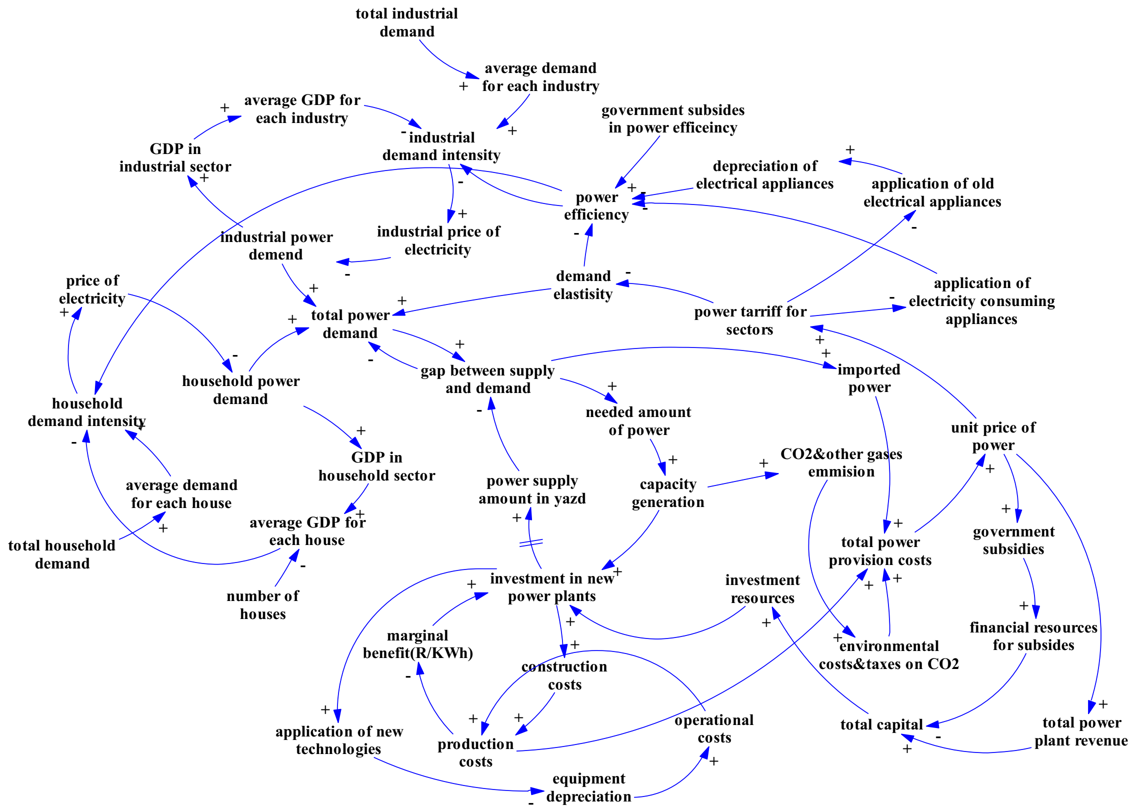

Fig. 2. A brief view of causal loop diagram for electricity system.

relation with GDP. Due to this relation, in this paper, GDP has been considered as an important input variable to analyze the future demand of electricity.

– ***Electricity demand intensity***: Demand intensity which is the other main variable in this subsystem shows the amount of electricity that is consumed to obtain one unit of GDP. It is obvious that the lower amount of demand intensity indicates the higher degree of electricity energy efficiency. In this research, the amounts of demand intensity in different sectors included domestic, industrial, service and agricultural sectors are considered to analyze the electricity demand in different sectors and the total electricity demand. Therefore, the reference electricity demands for different sectors are calculated as follows:

$$\text{ref elec dem} = GDP * \text{sector intensity} \quad (1)$$

In addition to the above-mentioned variables, three significant variables are the effect of technology development (TD), the effect of demand side management (DSM) and the effect of tariff on the electricity demand of different sectors. The following equations described the indicated electricity demand and the total electricity demand in different sectors:

$$\text{ind elec dem} = \text{ref elec dem} * \text{DSM eff} * \text{tariff eff} * TD \text{ eff} \quad (2)$$

$$\text{Total elec dem } (t+\Delta t) = \text{Total elec dem } (t) + \int_t^{\Delta t} \text{ind elec dem } (\tau) d\tau \quad (3)$$

These variables also have a significant effect on the amount of electricity peak demand which is the other main variable in this subsystem. Fig. 3 shows a general view of the stock-flow diagram of the electricity demand subsystem. It must be noted that for the sake of brevity, the other related variables in the subsystem are not represented.

4.2. Electricity generation subsystem

The main variables of the electricity generation subsystem are as follows:

- The considered power provision methods are concentrated generation (CG), distributed generation (DG), demand side management (DSM) and energy importing (EI). One of the main objectives of this study is to determine the shares of different methods of power provision. In other words, defining the portfolio of power provisions are one of the main desired outputs.
- ***Capital constraint***: The amount of investment is one of the main variables in the electricity generation subsystem. The fact that some of the required electricity generation capacities are not fully accessible due to the capital constraint, decrease the reliability of power generation. The amount of capacity shortage is calculated as follows:

$$\text{capacity shortage} = \text{capgap} - \text{concap} - \text{discap} - \text{imp} \quad (4)$$

where capgap, concap, discap and imp are represented the gap between needed and current capacity, developed concentrated power plants, developed distributed power plants and imported capacity, respectively.

- ***Power plants efficiency***: power plant efficiency is the other effective variable in power generation subsystem that shows the amount of time that a power plant is in use in a year.

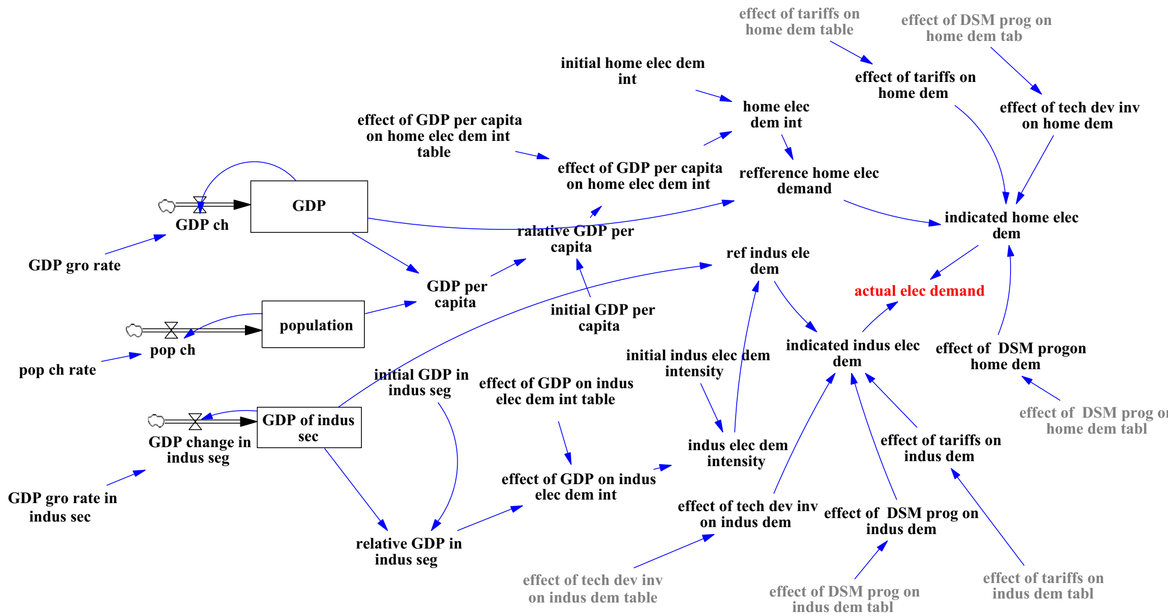

Fig. 3. Electricity demand subsystem.

Obviously, higher degrees of power plant efficiency cause lower amounts of new electricity generation capacities.

- ***Depreciation***: depreciation shows that what share of current electricity generation capacities are depreciated every year.
- ***Private sector share in power generation***: due to the limitation of government for investment in new power generation capacities and the low level of productivity in government power plants, the contribution of private sector is an undeniable part of the power generation subsystem. So far, the participation of Iranian private sector in power generation is not significant. However, in coming years, the increasing trend of power demand and the lack of government financial resources will enforce the government sector to give more roles to the private sector.

The main variables of the electricity generation subsystem are illustrated as a stock- flow diagram in Fig. 4.

4.3. Technology subsystem

Defining the weights of different technologies in the portfolio of power generation technologies is one of the main variables in this subsystem. In this paper, the gas, coal and solar based power plants are considered as the most appropriate options in Yazd [31]. Moreover, the amounts of investment in different technology development programs such as demand reduction, pollution reduction and increasing power plants efficiencies are the other important variables. Fig. 5a shows a general view of the main variables and their effects on the technology subsystem.

4.4. Environment subsystem

The environment subsystem is dealt with the environmental aspects of electricity generation system. The effect of technology development programs on the pollution reduction, the share of different technologies in power generation and the effect of different policies on the demand reduction are the most important variables in this subsystem. A general view of the environment subsystem is represented in Fig. 5b.

4.5. Price/tariff subsystem

The main purpose of price subsystem is to determine the unit price and tariff of electricity and analyze the effect of these variables on the other subsystems. The tariff adjustment rate (the share of electricity costs that the consumers should pay), the unit price of electricity considering the generated and imported electricity and the inflation rate, as an exogenous variable, are the main variables in this subsystem. The unit price of electricity and the electricity tariff are represented as follows:

$$UCE = (TCI + TCC + TCD)/TGE \tag{5}$$

$$\text{Tariff} = UCE * TAR \tag{6}$$

where UCE is the unit cost of electricity, TCI is the total cost of imported energy, TCC is the total cost of generated energy in concentrated power plants, TCD is the total cost of generated energy in distributed power plants, TGE is the total generated energy and TAR is the tariff adjustment rate. (The marginal profit ratio of electricity selling, which was below one in the base case conditions.)

On the other hand, the unit tariff of electricity has a straight effect on the amounts of demand, profit and investment. Fig. 6a presents the main variables and their relations in the price/tariff subsystem.

4.6. Regulation subsystem

In this subsystem, the endogenous variables that have regulatory aspects are considered. The tariff adjustment rate, the amount of investment on the demand side management and the technology development, the degree of privatization (amount of private sector participation) and the shares of different technologies in power generation are the main regulatory variables. Fig. 6b shows the main variables that influence on the regulatory subsystem.

4.7. Economical profit

In this subsystem, the amounts of incomes, costs and total capital are analyzed. Variables such as tariff, electricity demand, amounts of exported electricity and the effect of economical profit

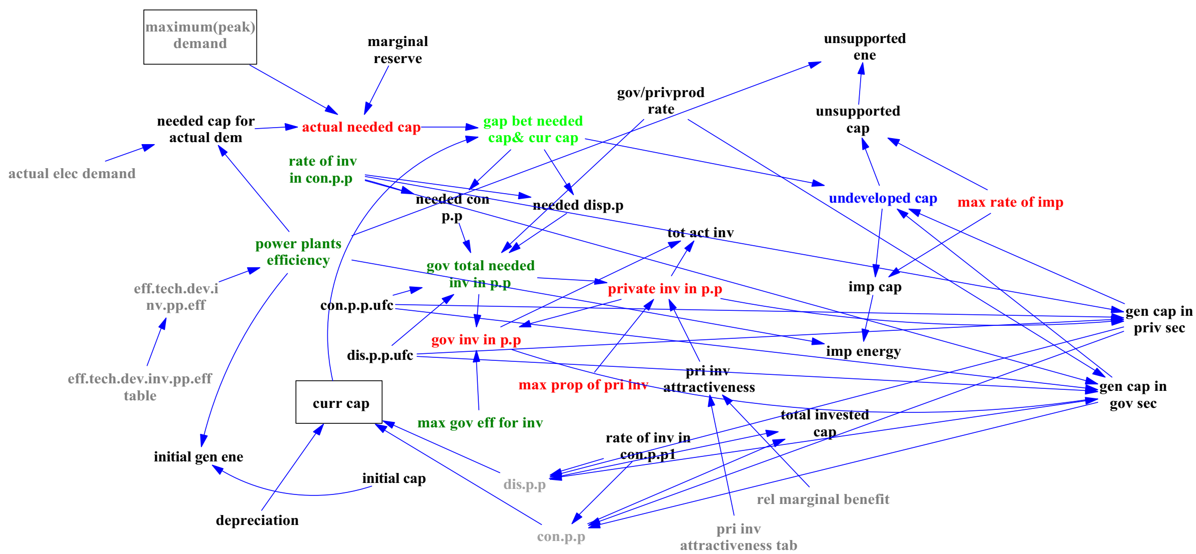

Fig. 4. Electricity generation subsystem.

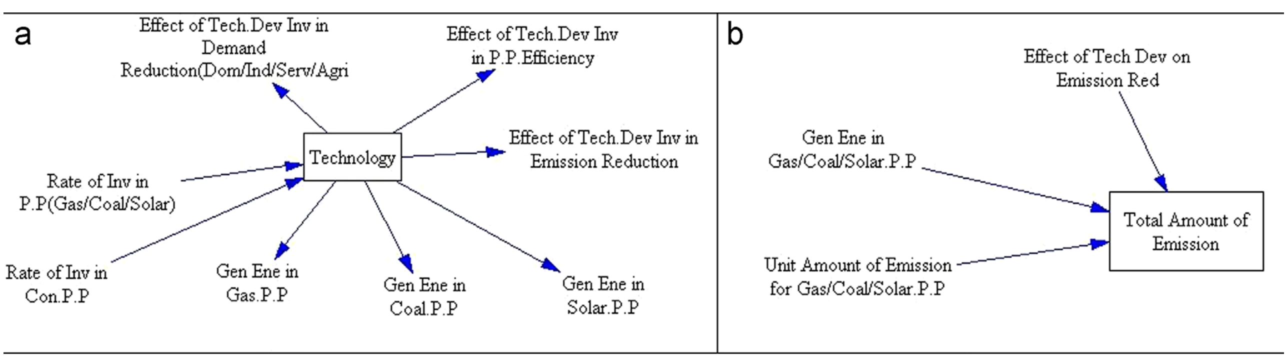

Fig. 5. (a) Technology subsystem and (b) environment subsystem.

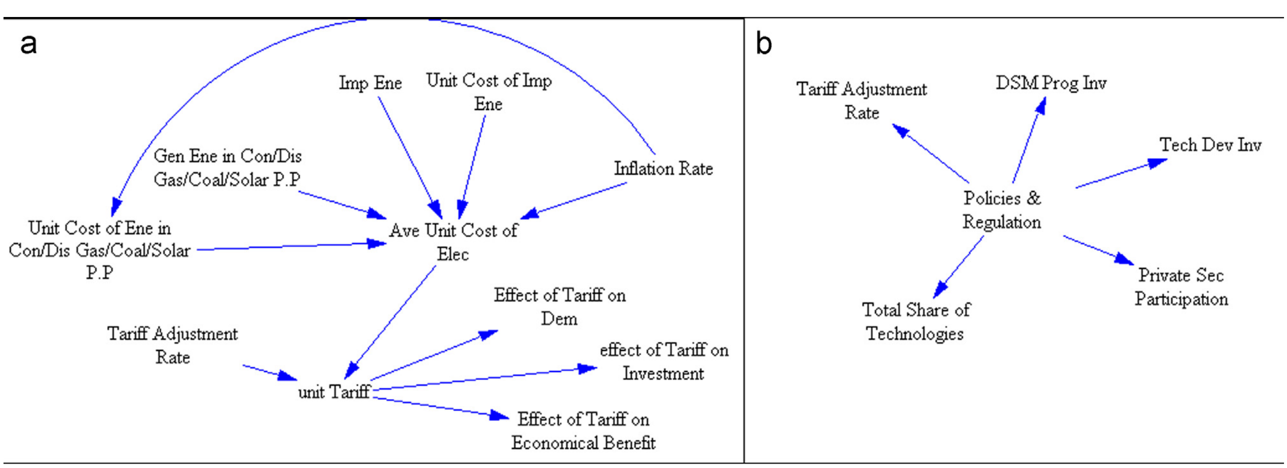

Fig. 6. (a) Price/Tariff subsystem and (b) regulation subsystem.

on investment are the main variables in this subsystem. In this subsystem, the total benefit for government is consisted of the private sector tax and the government benefit from electricity selling. The main variables of this subsystem are illustrated in Fig. 7.

4.8. Export/import subsystem

The maximum proportion of imported power is one of the main variables in this subsystem. This variable shows that what part of electricity demand can be provided through importing.

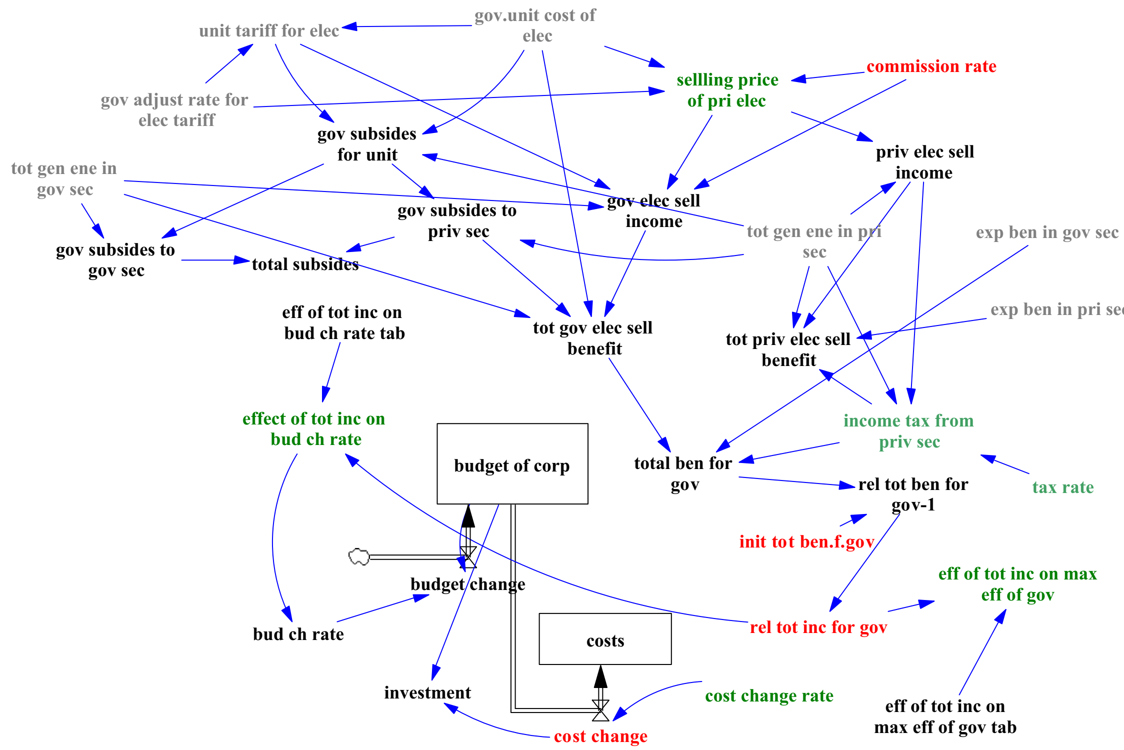

Fig. 7. Economical profit subsystem.

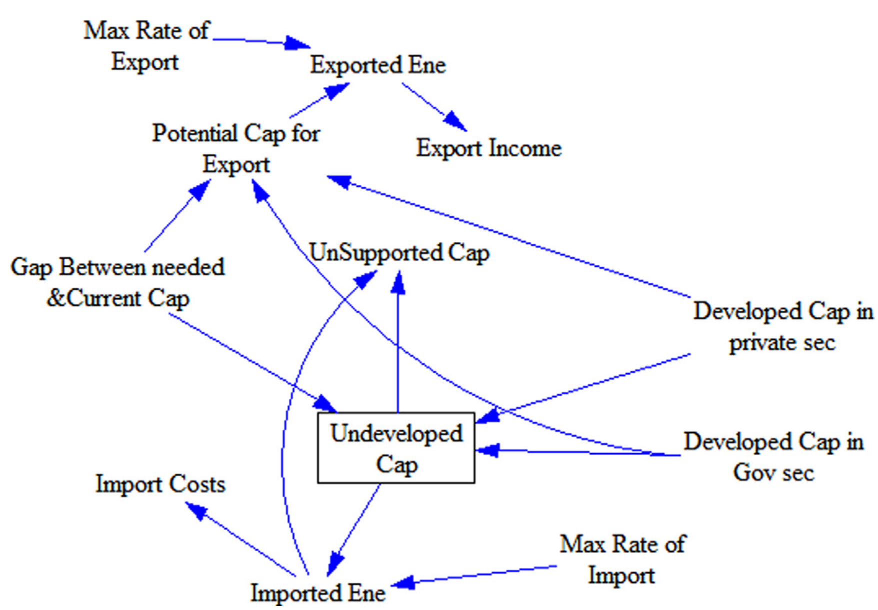

Fig. 8. Export/Import subsystem.

On the contrary, the maximum proportion of exported power which shows the share of out of work power plant capacities that can be exported is the other main variable in this subsystem. Moreover, the effects of power import and export on the economical profit are the other main variables in the export/import subsystem. Fig. 8 shows the main variables of the export/import subsystem.

4.9. Investment subsystem

The investment subsystem provides the required amount of capital for the other subsystems of electricity generation system. The amount of private sector participation, the degree of private sector interest in investment, the amount of investment in DSM and TD programs are the most important variables in this subsystem. The main variables of the investment subsystem with their relations are depicted in Fig. 9.

4.10. Demand side management subsystem

Analysis of the effect of investment in DSM programs on the electricity demand of domestic, industrial, service and agricultural sectors is the main objective of this subsystem. Even though DSM is an effective subsystem of electricity generation subsystem, the main variables of this subsystem are described in electricity demand Subsystem.

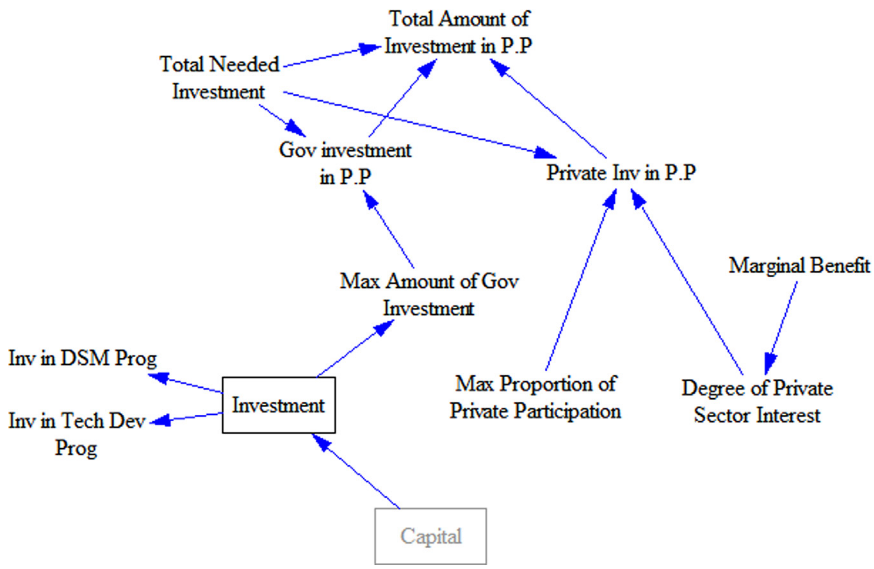

Fig. 9. Investment subsystem.

Table 1
The real demands compared with simulated demands.

	2002	2003	2004	2005	2006	2007	2008
Real domestic demand (GWh)	492	547	601	664	720	784	843
Simulated domestic demand (GWh)	527	624	692	728	741	748	801
Real industrial demand (GWh)	1250	1500	1460	1050	1190	1360	1470
Simulated industrial demand (GWh)	1350	1580	1650	1530	1300	1250	1370
Real service demand (GWh)	334	344	369	406	445	482	460
Simulated service demand (GWh)	337	394	438	460	470	456	494
Real agriculture demand (GWh)	381	424	486	525	537	544	578
Simulated agriculture demand (GWh)	385	439	486	526	562	600	647
Real total demand (GWh)	2160	2460	2810	2920	2650	2890	3170
Simulated total demand (GWh)	2160	2600	3040	3270	3250	3070	3050

It must be noted that there are no clear and distinct boundaries between the above mentioned subsystems. These unclear boundaries with the fact that there are different interactions between the subsystems make the overall system to be complex and unpredictable.

5. Validation of the model

In this section, the validity of the proposed model is evaluated based on the historical data for Yazd regional electricity company in the period 2001–2008. For this purpose, the year 2001 is considered as the base year and the simulation results of the model for the period 2001 to 2008 are compared with the real data. In this paper, for the sake of brevity, only the real amounts of electricity demand are compared with the results of the model. As the electricity demand is the main variable which affects all parts of the model, the appropriate results for the electricity demand make an approximate confidence on the results of the other parts of the model. Table 1 shows the results of the proposed model compared with the real data in the period 2001–2008 [31,32].

As it is shown in Table 1, the simulated results of the model have not a significant difference with the real amounts of demand; however in some cases, the model has had a lag in following the trends, but it could comprehend the trends effectively. Fig. 10 which compared the real total demand with the simulated total demand shows the power of the proposed SD model in comprehension of the behaviors of the system.

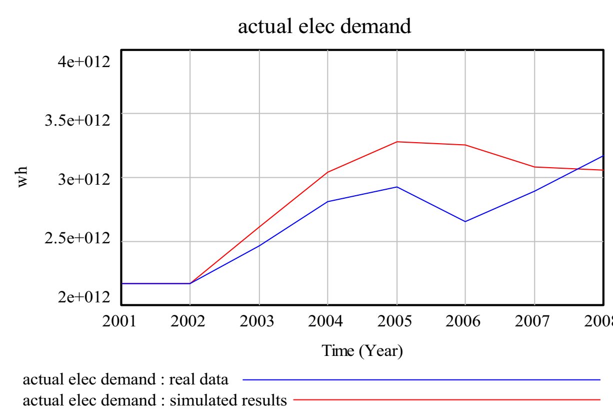

Fig. 10. Real total demand – simulated total demand.

6. Scenario and policy analysis

In this section, the results of RDIEM for different scenarios and policies in Yazd electricity supply system are analyzed. The scenarios are made with different amounts of exogenous variables that have significant effects on the outputs of the system. As it is shown in Fig. 1, the inflation rate and the GDP growth rate are two important exogenous variables. In this study, 5 different scenarios are created based on different amounts of the exogenous variables. The policies, on the other hand, are based on different amounts of endogenous variables. In this study, 5 different policies are selected with different amounts of tariff adjustment rate, share

Table 2
Proposed scenarios [32].

Scenarios	Characteristics
Scenario A (base case Scenario): assumes that the As Is conditions are preserved in the future.	Inflation rate = 10%, Total GDP growth rate = 0.263, Industrial GDP GR = 0.302, Service GDP GR = 0.257, Agricultural GDP GR = 0.198.
Scenario B	This scenario assumes that the inflation rate is increased to 20%. The other variables are preserved.
Scenario C	This scenario assumes that the inflation rate is decreased to 5%. The other variables are preserved.
Scenario D	This scenario assumes 50% increasing in the GDP growth rate for different sectors. The other variables are preserved.
Scenario E	This scenario assumes 50% decreasing in the GDP growth rate for different sectors. The other variables are preserved.

Table 3
Proposed policies.

Policies	Characteristics
Policy 1 (base case Policy): assumes that the As Is conditions are preserved.	Tariff adjustment rate: 43%; Share of Government investment = 100%; Share of DSM and TD investment = 1% of budget; Share of gas power plants = 100%.
Policy 2 (Government-Oriented Policy): assumes that government tries to preserve its dominance in power generation, But the electricity selling tariffs are adjusted in favor of government.	Tariff adjustment rate: 120%; Share of Government investment = 100%; Share of DSM and TD investment = 1% of budget; Share of gas power plants = 50%; Share of coal-fired power plants = 50%.
Policy 3 (Private Sector-Oriented Policy): assumes that government tries to decrease its dominance in power generation and improve its regulatory and controlling roles.	Tariff adjustment rate: 120%; Share of Government investment = 25%; Share of DSM and TD investment = 1% of budget; Share of gas power plants = 70%; Share of coal-fired power plants = 25%; Share of solar power plants = 5%.
Policy 4 (Environment-Oriented Policy): environment conservation and decreasing power generation pollution are the main objectives of this policy.	Tariff adjustment rate: 140%; Share of Government investment = 25%; Share of DSM and TD investment = 10% of budget; Share of gas power plants = 80%; Share of coal-fired power plants = 0%; Share of solar power plants = 20%.
Policy 5 (Balanced Growth Policy): assumes balanced amounts for different variables to obtain balanced results in different aspects.	Tariff adjustment rate: 100%; Share of Government investment = 50%; Share of DSM and TD investment = 5% of budget; Share of gas power plants = 75%; Share of coal-fired power plants = 25%; Share of solar power plants = 0%.

of government sector in power generation, the amount of investment in DSM and TD and the share of different technologies in power generation. The combination of scenarios and policies makes a comprehensive way to understand the behaviors of the considered electricity system.

6.1. Scenarios and policies description

Scenarios are the combination of different amounts of exogenous variables which are not under the control and management of electricity supply systems. The analysis of the behavior of the system for different scenarios helps the policy makers to extract the most relative policies for the possible changes in the system environment. In the scenario extraction, the extreme values of the three main exogenous variables are combined to make 5 extreme scenarios. Table 2 represent the considered scenarios for the electricity supply system in Yazd province. Scenario A which is the base case scenario assumes that the inflation rate, the nominal GDP growth rate of different economical sectors and the technologies are preserved the same in the future. Owing to some structural problems and international pressures, the inflation rate is the main obstacle of economical development in Iran in recent years. The next two scenarios (B and C) are considered the extreme values of inflation rate with preserving other variables. On the other hand, the scenarios D and E are assumed a 50% increase and decrease in the economical growth rate of different sectors and other variable are assumed to be preserved.

With assuming different scenarios for the system, the policy makers should design different combinations of endogenous variables (policies), which are under the control of electricity supply system, according to the different scenarios. In the policy making process, the expert viewpoints and regional electricity company manuscripts are considered. Table 3 shows the considered policies to analyze the electricity supply system in Yazd province. Policy 1 (base case policy) assumes that the current conditions of variables are preserved. Therefore, in this policy, the government continues to give the power subsidies to different sectors and holds its control on the whole electricity system. Policy 2, which is named the government oriented policy, assumes that the government omits its power subsidies and tries to make profit from the electricity supply system besides to preserve its dominance in power generation. Therefore the government tries to maximize its electricity selling with low cost and high pollutant power generation technologies and makes the minimum amount of demand side management and technology development investment. In policy 3, the government reduces its share in the power plant investment and limits its share to 25% of the needed capacity. In Policy 4, which is named as an environment-oriented policy, the main objective of policy makers is to conserve the environment with increasing the power tariff and demand side management and technology management investment as well as changing the power generation technologies to the cleaner technologies. In balance growth policy (policy 5), the extreme values of the variables in other policies are adjusted to balanced values in order to achieve a satisfying results in all aspects and minimizing the social effects of the other policies.

In order to analyze the performance of different scenarios and policies, 4 different performance indices are taken into account. Accordingly, the amounts of pollution and the amount of capacity shortage are considered as the environmental and technical performance indices. Moreover, the unit cost of electricity and the amount of economical profit are the economical performance

indices. In addition to these indices, the electricity demand and the amount of supplied capacities are the other variables that have been considered for the analysis of the results.

6.2. The analysis of the scenarios and policies

Considering 5 different scenarios and policies, there are 25 different instances of the combination of scenarios and policies. According to the 6 mentioned performance indices and 25 different instances, 150 different results should be represented in this section. In this section, for the sake of brevity, a brief review of the results of 6 performance indices for different 25 instances in the period 2010–2020 are represented.

6.2.1. Electricity demand

Table 4 shows the maximum and minimum amounts of electricity demand in 2020 for different scenarios. As it is shown in Table 4, the maximum amount of electricity demand in all scenarios is happened in policy A (Base case policy). On the contrary, the environment-oriented Policy (policy D) which has had the maximum share of DSM and TD investment and maximum amount of tariff adjustment rate has minimum amounts of electricity demand in all scenarios. For instance, in the base case scenario, the amount of electricity demand for policy 4 is 40% lower than the base case policy.

On the other side, scenarios D and E, which have had the maximum and minimum GDP growth rate, have maximum and minimum amounts of electricity demand, respectively. The minimum expected demand of these scenarios show 98% and −74% change compared with the base case scenarios. Moreover, scenario C which has had the minimum inflation rate, have also a high amount of electricity demand.

6.2.2. Supplied capacity

Apart from the amounts of electricity demand and peak demand, the capital constraint is a main effective variable on the amount of supplied capacity. As it is obvious in Table 5, the minimum amounts of supplied capacities in all scenarios are occurred in the base case policy, which has inclined to the government financial resources. According to the existing capital constraints in the government sector, a noticeable amount of needed capacities have not been developed in the base case and the government-oriented policies; nevertheless, the maximum amount of supplied capacities is obtained through the balanced growth policy (policy 5). Moreover, among different scenarios, the maximum and minimum amounts of supplied capacities are in scenarios D and E, respectively.

6.2.3. Capacity shortage

As it is mentioned in the analysis of supplied capacity that the base case and government-oriented policies have had the minimum amounts of supplied capacities, these policies have also the huge amounts of capacity shortage in all scenarios. As it is shown in Table 6, the maximum amounts of capacity shortage are obtained in the base case policy; indeed, the maximum amount of capacity shortage in base case scenario is 380 MW which is increased to 1050 MW in scenario D. Conversely, there are no amounts of capacity shortage in the other policies which have the private sector participation.

6.2.4. Unit cost of electricity

Based on the results of the base case scenario, the maximum and minimum unit cost of electricity in 2020 will be 2490 (R/KWh) and 2020 (R/KWh), respectively. Table 7 shows the amounts of unit cost of electricity for different scenarios and policies. As it is

Table 4
The results of electricity demand in different scenarios.

Scenario	Max expected demand (wh)	Max related policy	Change (%)	Min expected demand (wh)	Min related policy	Change (%)
Scenario A (base case)	8.7E 12	Base case policy	0	5.22E 12	Policy 4	−40
Scenario B	8.23E 12	Base case policy	−5	5.22E 12	Policies 3, 4	−40
Scenario C	1.01E 13	Base case policy	16	5.27E 12	Policy 4	−39
Scenario D	2.87E 13	Base case policy	> 200	1.72E 13	Policy 4	98
Scenario E	3.72E 12	Base case policy	−57	2.28E 12	Policy 4	−74

Table 5
The results of supplied capacity in different scenarios.

Scenario	Max supplied capacity (w)	Max related policy	Change (%)	Min supplied capacity (w)	Min related policy	Change (%)
Scenario A (base case)	1.43E 09	Policy 5	> 125	6.33E 08	Base case policy	0
Scenario B	1.39E 09	Policy 5	> 100	6.33E 08	Base case policy	0
Scenario C	1.47E 09	Policy 5	> 125	6.33E 08	Base case policy	0
Scenario D	2.46E 09	Policy 5	> 275	6.33E 08	Base case policy	0
Scenario E	1.43E 09	Policy 5	> 125	6.33E 08	Base case policy	0

Table 6
The results of capacity shortage in different scenarios.

Scenario	Max capacity shortage (w)	Max related policy	Change (%)	Min capacity shortage (w)	Min related policy	Change (%)
Scenario A (base case)	3.58E 08	Base case policy	0	0	Policies 3, 4, 5	−10
Scenario B	3.12E 08	Base case policy	−13	0	Policies 3, 4, 5	−100
Scenario C	3.87E 08	Base case policy	8	0	Policies 3, 4, 5	−100
Scenario D	1.05E 09	Base case policy	> 175	0	Policies 3, 4, 5	−100
Scenario E	3.51E 08	Base case policy	−2	0	Policies 3, 4, 5	−100

obvious in Table 7, the minimum and maximum unit cost of electricity will occur in the balanced growth policy and base case policy, respectively. The high amount of cheap coal-based power plants with the lack of expensive solar electricity tends the balanced growth policy to the lowest unit cost of electricity. On the contrary, although the base case policy has only focused on gas power plant, the high amounts of imported electricity makes the high unit cost of electricity.

In another view, the minimum and maximum unit price of electricity will be in scenario C and B with 5% and 20% inflation rate, respectively. Based on the results, the minimum unit price of electricity in 2020 will be 1100 (R/KWh) in scenario C and the maximum one will be 6840 (R/KWh) in scenario B.

6.2.5. Economical profit

The low level of tariff in the base case policy which is lower than 50% of unit cost of electricity causes a huge amount of government subsidies. In other words, by the base case policy in all the scenarios, the regional electricity company has a great amount of loss. Moreover, a higher amounts of electricity demand leads to a higher amount of loss; therefore, the amount of loss is maximized in scenario D. On the other hand, the other policies which their tariffs are higher than the unit cost of electricity, convert the Yazd electricity system to a profitable system. As it is shown in Table 8, the maximum amount of profit is occurred in the environment-oriented policy. Even though the 140% tariff adjustment rate in the environment-oriented policies has decreased the amount of electricity demand, it leads to a higher amount of marginal and total profit.

On the other side, the high amount of unit cost of electricity and tariff adjustment rate cause scenario B to have the highest amounts of profit. Scenario D, which has the highest amount of electricity demand, also has a high level of profit. On the other hand, scenario C with a low level of demand and tariff has the minimum amounts of profit as well as the minimum amounts of loss in base case policy.

Table 7
Unit price of electricity in different scenarios.

Scenario	Max price (Rial/Wh)	Max related policy	Change (%)	Min price (Rial/Wh)	Min related policy	Change (%)
Scenario A (base case)	2.49	Base case policy	0	2.02	Policy 5	−19
Scenario B	6.84	Base case policy	175	6.28	Policy 5	150
Scenario C	1.48	Base case policy	−41	1.1	Policy 5	−56
Scenario D	2.79	Base case policy	12	2.02	Policy 5	−19
Scenario E	2.49	Base case policy	0	2.02	Policy 5	−19

6.2.6. Amounts of pollution

As it is shown in Table 6, as expected, the environment-oriented policy will have the minimum amounts of pollution. As it is represented in Table 9, this scenario causes a 30% reduction in the amount of pollution in comparison with the balance growth policy, which has the highest amount of pollutants. It must be noted that the balance growth policy, which have the highest amount of pollutions, have provided all the amounts of electricity demand; while in the base case policy, more than 50% of needed electricity in 2020 will be imported or will not be provided. Considering the scenarios, scenarios B and D have the maximum amount of demand and consequently maximum amounts of pollution.

6.2.7. Optimal policy

As it is shown in Tables 4–9, two policies 4 and 5 (environment-oriented and balanced growth policies) represent the best results among different policies. Table 10 shows the best and worst values of different indices in 25 different instances of the model. As it is obvious, the environment-oriented policy has minimum amounts of pollution as well as minimum amount of electricity demand, maximum amounts of total profit and minimum amounts of capacity shortage. In other words, the minimum amounts of pollution in environment-oriented policy is not only because of the application of solar power plants and omission of coal-fired power plants, but also because of the demand reduction resulting from the maximum amount of investment in DSM and TD and the maximum amount of tariff adjustment rate.

On the other hand, as the balanced growth policy has not huge amounts of electricity demand and pollution, it has a minimum unit cost of electricity as well as maximum amounts of supplied capacity and minimum amounts of capacity shortage among policies. Considering the base case scenario as the more likely scenario, Fig. 11 compares the total electricity demand, total capacity shortage and total amounts of GHG emissions of environment-oriented and the balanced growth policies.

Although the environment-oriented and balance growth policies are the best policies, the final decision on the optimal policy is thoroughly dependent on the decision maker's preferences. In other words, the selection of optimal policy is a multiple criteria

Table 9
Amounts of pollution in different scenarios.

Scenario	Max pollution (gr)	Max related policy	Change (%)	Min pollution (gr)	Min related policy	Change (%)
Scenario A (base case)	8.33E 12	Policy 5	0	5.8E 12	Policy 4	−30
Scenario B	8.16E 12	Policy 5	−2	5.63E 12	Policy 4	−32
Scenario C	8.54E 12	Policy 5	3	5.95E 12	Policy 4	−29
Scenario D	1.43E 13	Policy 5	72	9.2E 12	Policy 4	10
Scenario E	6.2E 12	Policy 5	−26	4.4E 12	Policy 4	−47

Table 8
Economical profit in different scenarios.

Scenario	Max profit (Rial)	Max related policy	Change (%)	Min profit (Rial)	Min related policy	Change (%)
Scenario A (base case)	9.2E 12	Policy 4	> 150	−1.46E 13	Base case policy	0
Scenario B	2.82E 13	Policy 4	> 275	−3.81E 13	Base case policy	> −150
Scenario C	5.28E 12	Policy 4	> 125	−9.07E 12	Base case policy	38
Scenario D	1.82E 13	Policy 4	225	−2.83E 13	Base case policy	−94
Scenario E	9.2E 12	Policy 4	0	−1.46E 13	Base case policy	0

Table 10
Pessimistic and optimistic values of different indices.

Performance index	Pessimistic value	Related scenario and policy	Optimistic value	Related scenario and policy
Energy demand	2.78E 13	Scenario D, base case policy	2.28E 12	Scenario E, Policy 4
Supplied capacity	6.33E 8	All scenarios, base case policy	2.46E 9	Scenario D, Policy 5
Capacity shortage	1.05E 9	Base case scenario, Policy 4	0	All Scenarios, Policies 3, 4, 5
Unit cost	6.84	Scenario B, base case policy	1.1	Scenario C, Policy 5
Total profit	−3.81E 13	Scenario B, base case policy	2.82E 13	Scenario B, Policy 4
Pollution	1.43E 13	Scenario D, Policy 5	4.4E 12	Scenario E, Policy 4

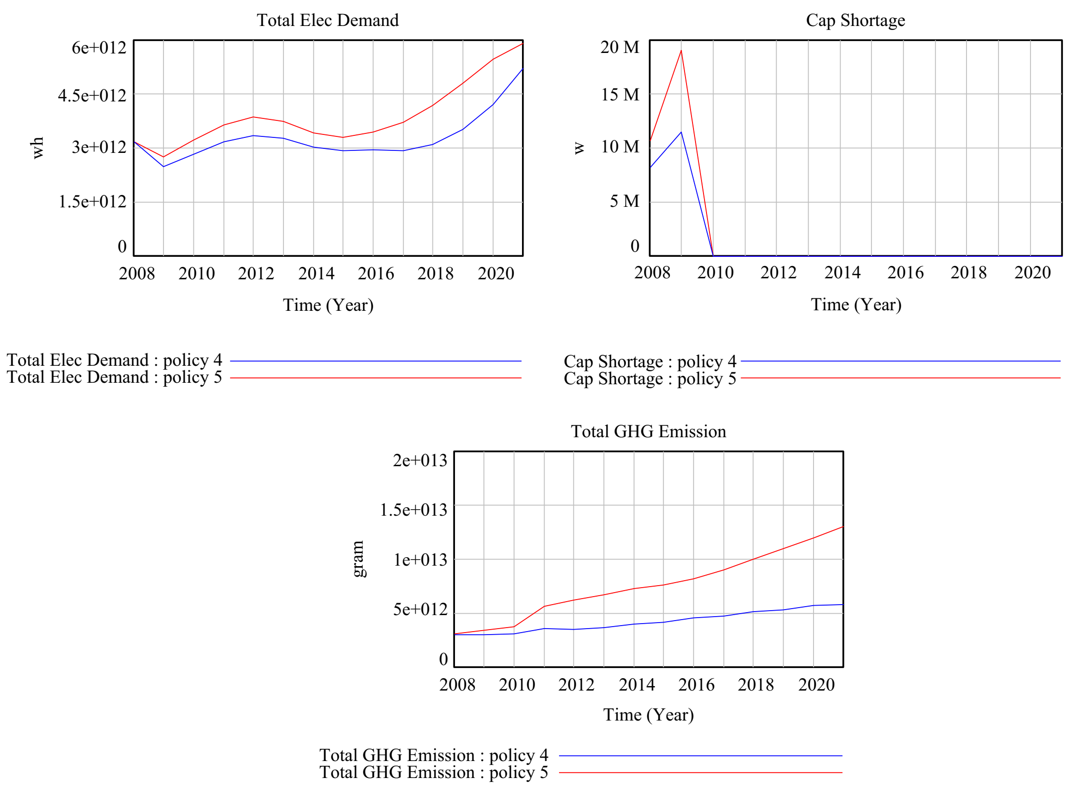

Fig. 11. Environment-oriented vs. balanced growth policy.

decision making problem according to the weights of different indices.

7. Concluding remarks

In this paper, a comprehensive SD-based model named RDIEM, containing all different subsystems of a regulated electricity system is introduced. The validity of the proposed model was evaluated based on the historical data from Yazd regional electricity company during the period 2000–2008. Five different scenarios and policies were taken into account.

The model was tested according to different environmental, technical and economical indices. The results show that the environment-oriented and balanced growth policies have the best results among different policies. The results of the environment-oriented policy in comparison with the base case policy show 40% reduction in the electricity demand, 100% decrease in the capacity shortage, more than 150% increase in economical profit and 30% reduction in the amount of pollution. Instead, the balanced growth policy causes more than 125% growth in the supplied capacity, 100% decline in the capacity shortage and 19% decrease in the unit cost of electricity.

Although the model was checked for a limited number of scenarios and policies, it has the potential to be tested with other options. The model is also flexible enough to be generalized to the similar problems in the domain of electricity supply systems. In other words, Even though the application is to the Iranian Case, the implications are much wider, especially in the developing countries.

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References

[1] Dementjeva N. Energy planning models analysis and their adaptability for estonian energy sector [Thesis on Mechanical and Instrumental Engineering]. 2009.
[2] Fenhann J. Case study with the energy-supply model EFOM-12C. Luxembourg; 2008.

[3] Wenying C. The costs of mitigating carbon emissions in China: findings from China MARKAL-MACRO modeling. Energy Policy 2005;33:885–96.
[4] Ramachandra TV. RIEP: regional integrated energy plan. Renew Sustain Energy Rev 2009;13:285–317.
[5] LEAP group. Long-range Energy Alternatives Planning System (LEAP) User Guide. Stockholm, Sweden; 2006.
[6] Pina A, Silva C, Ferrao P. Modeling hourly electricity dynamics for policy making in long-term scenarios. Energy Policy 2011;39:4692–702.
[7] European Union: results from the MIDAS model. European Comission Report. Austria; 1996.
[8] Xiaohua W, Yunrong H, Xiaqing D, Yuedong Z. Analysis and simulation on rural energy-economy system on Shouyang County in China. Renew Sustain Energ Rev 2006;10:139–51.
[9] Forrester J. Industrial dynamics. Waltham, MA: Pegasus Communications; 1961.
[10] Naill RF. The discovery life cycle of finite resource: a case study of U.S. natural gas. Cambridge, MA: MIT Press; 1973.
[11] Sterman JD. The energy transition and economy: a system dynamic approach [Ph.D Thesis]. MIT Press, Cambridge: MA; 1981.
[12] Naill RF. A system dynamics model for national energy policy planning. Syst Dyn Rev 1992;8:1–19.
[13] Naill RF, Belanger S, Klinger A, Petersen E. An analysis of the cost effectiveness of U.S. energy policies to mitigate global warming. Syst Dyn Rev 1992;8:111–28.
[14] Rahn J. A system dynamics model for long range electric utility planning: implementation experience. Dynamica 1981;7:32–5.
[15] Ford A. System dynamics and the electric power industry. Syst Dyn Rev 1997;13:57–85.
[16] Moxnes E. Interfuel substitution in OECD – European electricity production. Syst Dyn Rev 1990;6:44–65.
[17] Lomi A, Larsen ER. Strategic implications of deregulation and competition in the electricity industry. Eur Manag J 1999;17:151–63.
[18] Larsen ER, Bunn DW. Deregulation in electricity: understanding strategic and regulatory risk. J Oper Res Soc 1999;50:337–44.
[19] Qudrat-Ullah H, Davidsen PI. Understanding the dynamics of electricity supply resources and pollution: Pakistan's case. Energy 2001;26:595–606.
[20] Qudrat-Ullah H. MDESRAP: a model for understanding the dynamics of electricity supply, resources and pollution. Int J Global Eng 2005;23:1–14.
[21] Ford A. Cycles in competitive electricity markets: a simulation study of the western United States. Energy Policy 1999;27:637–58.
[22] Ford A. Waiting for the boom: a simulation study of power plant construction in California. Energy Policy 2001;29:847–69.
[23] Olsina F, Garces F, Haubrich HJ. Modeling long-term dynamics of electricity markets. Energy Policy 2006;34:1411–33.
[24] Ford A. Simulation scenarios for rapid reduction in carbon dioxide emissions in the western electricity system. Energy Policy 2008;36:443–55.
[25] Kilanc GP, Or I. A system dynamics model for the decentralized electricity market. Int J Simul 2011;7:40–55.
[26] Hasani M, Hosseini SH. Dynamic assessment of capacity investment in electricity market considering complementary capacity mechanisms. Energy 2011;36:277–93.
[27] Trappey AJC, Trappey CV, Lin GYP, Chang YS. The analysis of renewable energy policies for the Taiwan Penghu island administrative region. Renew Sustain Energy Rev 2012;16:958–65.
[28] Chang PL, Ho SP, Hsu CW. Dynamic simulation of government subsidy policy effects on solar water heaters installation in Taiwan. Renew Sustain Energy Rev 2013;20:385–96.
[29] Energy Ministry of Iran. Iran Energy Statistics report. Tehran, Iran; 2000–2009.
[30] Tavanir Co. Tavanir Statistical report. Tehran, Iran; 2009–2009.
[31] Yazd Regional Electricity Company. Yazd electricity Statistics. Yazd, Iran; 2009–2009.
[32] Iran statistics center. Yazd Statistical indices. Yazd, Iran; 2000–2010.